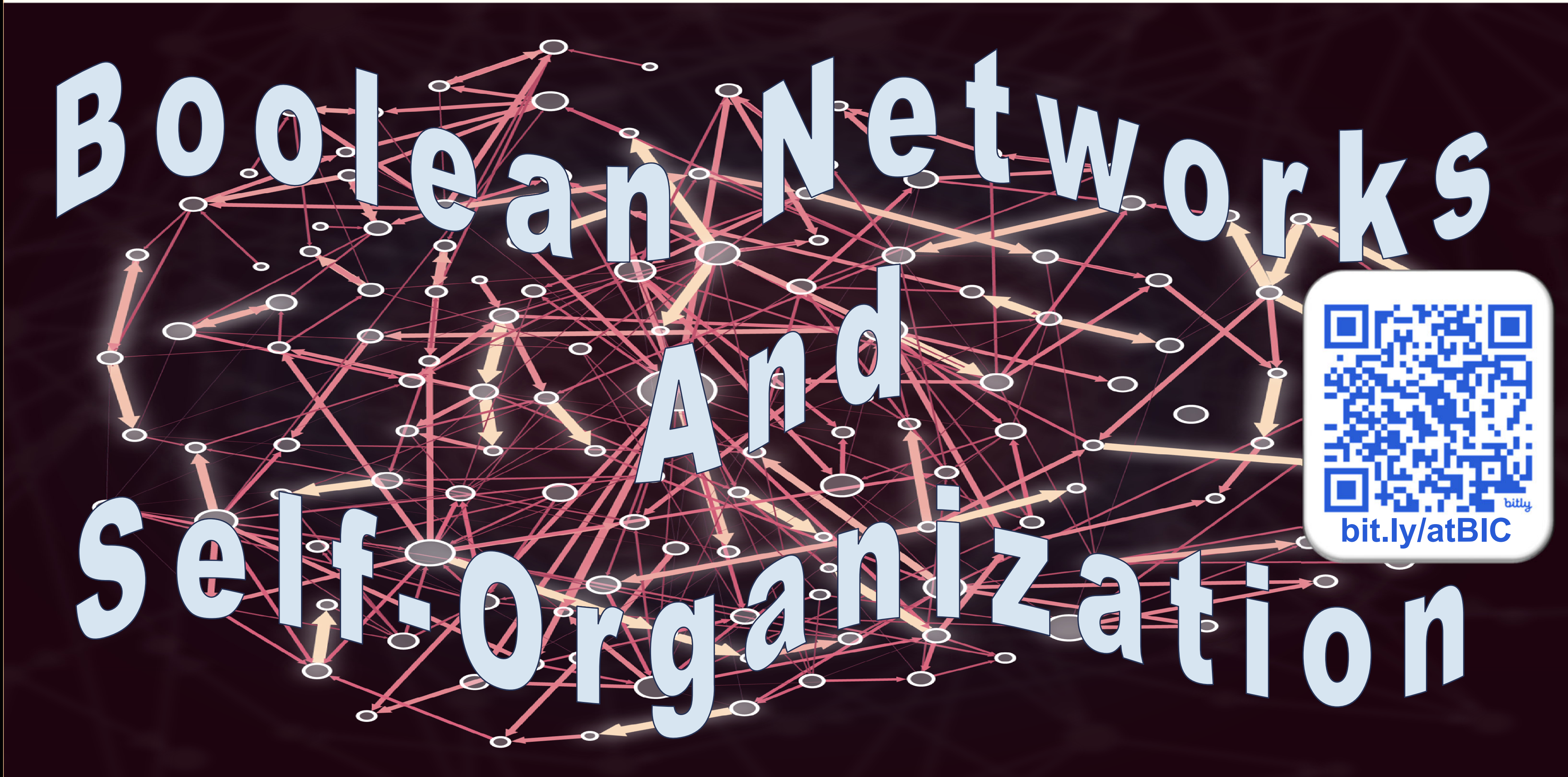
lecture 9

Boolean Networks And Self-Organization



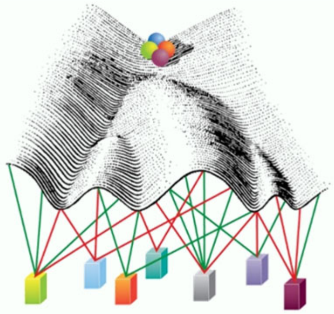
key events coming up

- Labs: 35% (ISE-483)
  - Complete 5 (best 4 graded) assignments based on algorithms presented in class
    - Lab 2 : February 19th
      - *L-Systems* (Assignment 2)
        - Delivered by SSIE583 Group 1
        - Due: February 26th
    - Lab 3: March 11th
      - Cellular Automata and Boolean Networks (Assignment 3)
        - Delivered by SSIE583 Group 3
        - Due: March 18th
- SSIE – 583 -Presentation and Discussion: 25%
  - Present and lead the discussion of an article related to the class materials
    - Enginet students post/send video or join by Zoom
  - February 26th
    - Kauffman, S.A. [1969]. "Metabolic stability and epigenesis in randomly constructed genetic nets". *Journal of Theoretical Biology* **22**(3):437-467.
      - Yoshiaki Fujita
  - Dates TBA
    - Conrad, M. [1990]. "The geometry of evolution.“ *Biosystems* **24**: 61-81.
      - Mario Franco
    - Stanley, Kenneth O., Jeff Clune, Joel Lehman, and Risto Miikkulainen. “Designing Neural Networks through Neuroevolution.” *Nature Machine Intelligence* **1**, no. 1 (January 2019): 24–35.
      - Jessica Lasebikan
    - Discussion by all

bit.ly/atBIC

until now

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press. Preface**, Sections 4.1, 4.2, Chapter 2.**
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall. **Chapter 1,** pp. 1-23. Chapter 7, sections **7.1-7.4**, **Appendix B.3.1**, **Chapter 2**, Chapter 8, sections **8.1, 8.2, 8.3.10**
- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
  - Chapter 4: Self-Organization and Emergent Complex Behavior
    - posted online @ http://informatics.indiana.edu/rocha/i-bic



- Papers and other materials
  - Dynamical Systems
    - Kauffman, S.A. [1969]. "Metabolic stability and epigenesis in randomly constructed genetic nets". Journal of Theoretical Biology 22(3):437-467.
  - Optional
    - Prusinkiewicz and Lindenmeyer [1996] *The algorithmic beauty of plants*.
      - Chapter 1
    - Flake's [1998], *The Computational Beauty of Life*. MIT Press.
      - Chapters 10, 11, 14 – Dynamics, Attractors and chaos

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until now

- Class Bo
  - Florea … ds, and Technologies. MIT Press.
    Prefa
    - N … hms, and Applications. Chapman & Hall.
      C … ns 8.1, 8.2, 8.3.10
- Lecture
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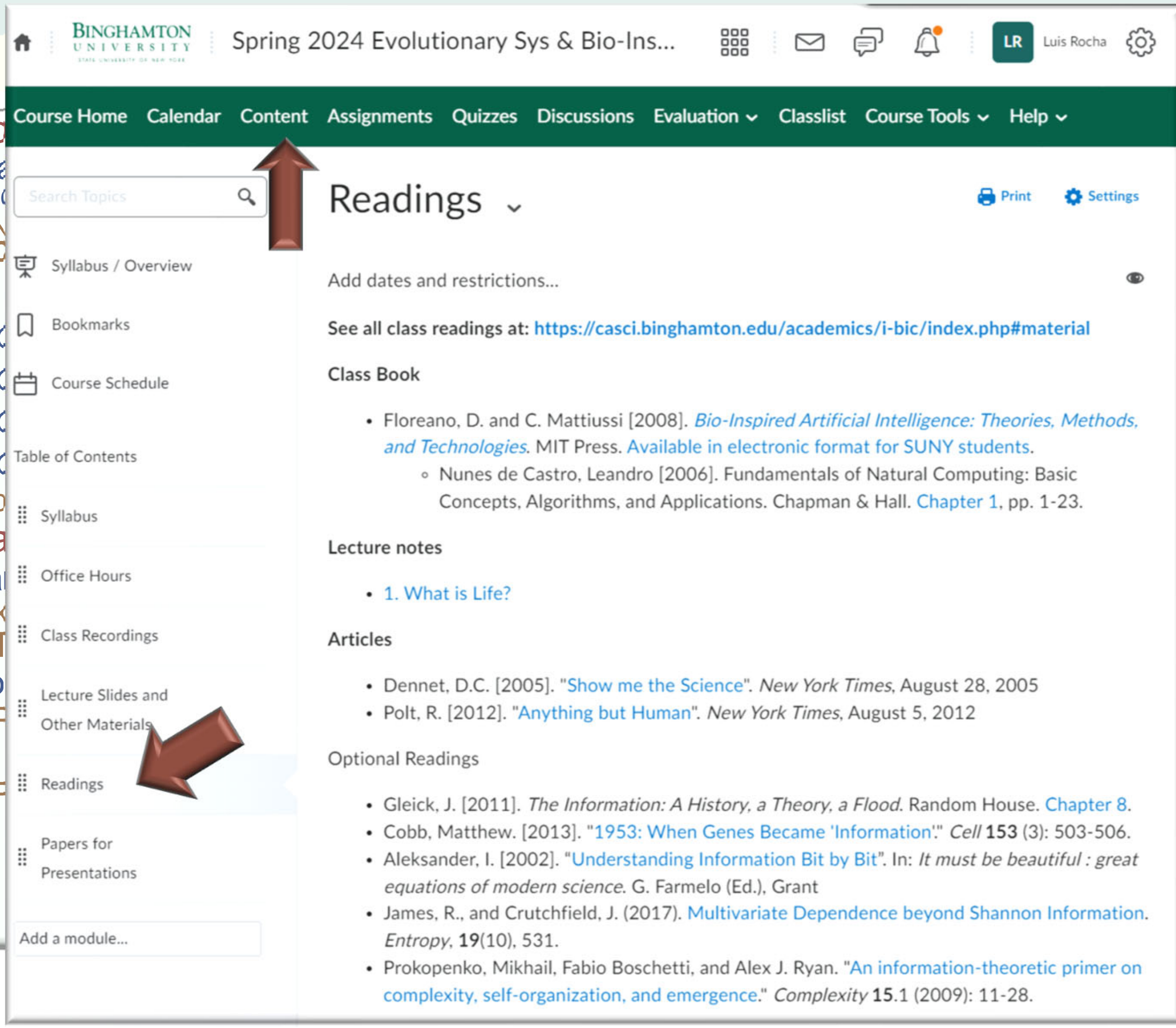

Spring 2024 Evolutionary Sys & Bio-Ins...

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See all class readings at: https://casci.binghamton.edu/academics/i-bic/index.php#material

Class Book

- Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press. Available in electronic format for SUNY students.
  - Nunes de Castro, Leandro [2006]. Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications. Chapman & Hall. Chapter 1, pp. 1-23.

Lecture notes

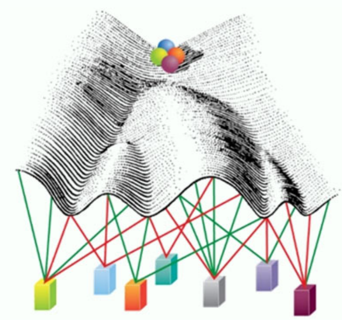
- 1. What is Life?

Articles

- Dennet, D.C. [2005]. "Show me the Science". *New York Times*, August 28, 2005
- Polt, R. [2012]. "Anything but Human". *New York Times*, August 5, 2012

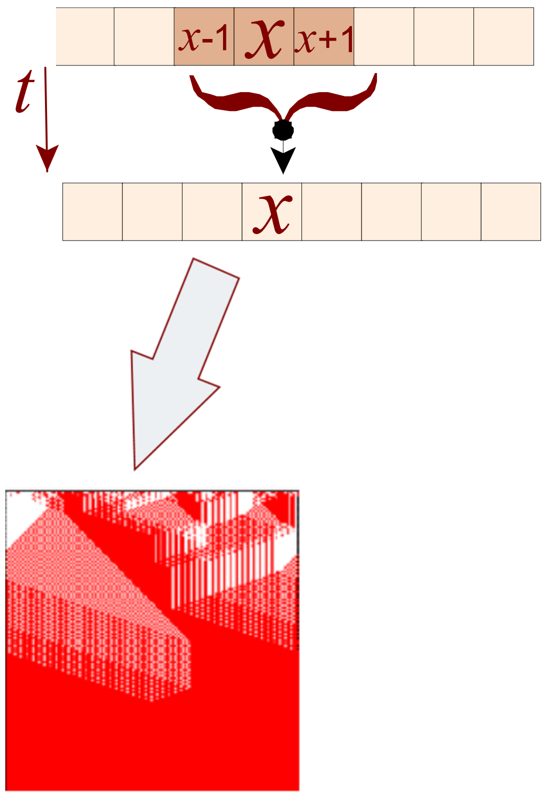
Optional Readings

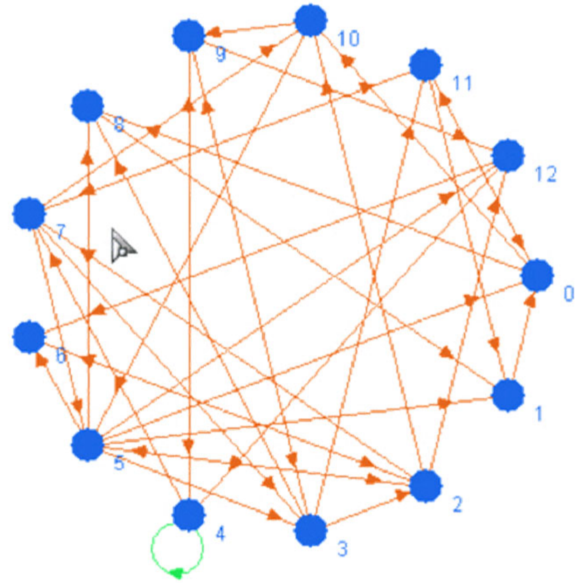
- Gleick, J. [2011]. *The Information: A History, a Theory, a Flood*. Random House. Chapter 8.
- Cobb, Matthew. [2013]. "1953: When Genes Became 'Information'." *Cell* **153** (3): 503-506.
- Aleksander, I. [2002]. "Understanding Information Bit by Bit". In: *It must be beautiful : great equations of modern science*. G. Farmelo (Ed.), Grant
- James, R., and Crutchfield, J. (2017). Multivariate Dependence beyond Shannon Information. *Entropy*, **19**(10), 531.
- Prokopenko, Mikhail, Fabio Boschetti, and Alex J. Ryan. "An information-theoretic primer on complexity, self-organization, and emergence." *Complexity* **15**.1 (2009): 11-28.



examples

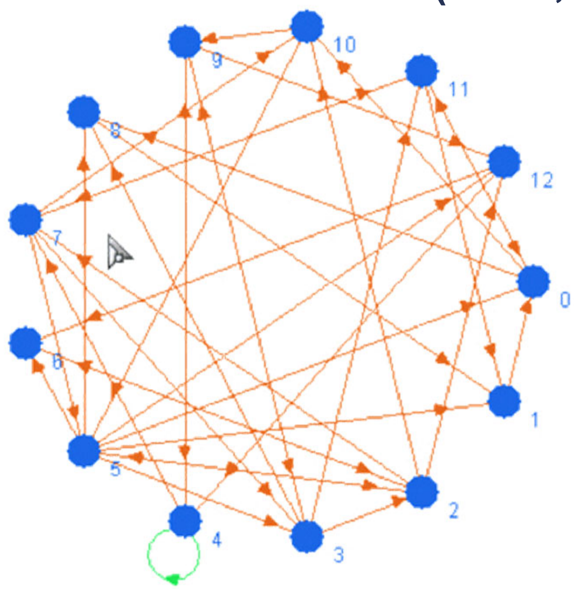
Cellular Automata





NK Boolean Network (N=13, K=3)

NK Boolean Network (N=13, K=3)



$$\prod_{i=1}^{N} 2^{2^{k_i}}$$

different Boolean networks for same structure (256^{13})

$2^N \rightarrow$ Network configurations (state-space)

$2^{2^K} \rightarrow$ possible Boolean functions of k inputs (k=3 →256)

Multivariate Dynamical Systems:
Structure: Variable interactions, associations, influence
Dynamics: variable *states* (micro) network *configurations* (macro)
Redundancy: links (path backbones), state transitions (**canalization**)

Minimal networks with both structure and dynamics. Interactions and variables with binary states. Huge state-spaces and ***ensembles*** for same structure. Full range of **attractor behavior**

Kauffman, SA. *J. theoretical biology* **22**.3 (1969): 437-467.

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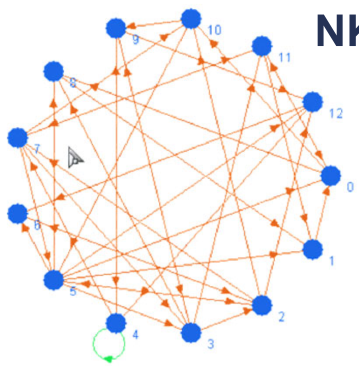
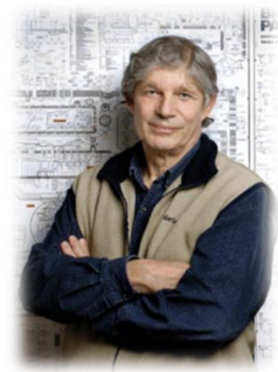
Stuart Kauffman's version



NK Boolean Network (N=13, K=3)

N: #nodes (Boolean variables)

K: # of inputs per node



$2^K \rightarrow$ possible input combinations for an automaton node

K=2

x1	x2
0	0
0	1
1	0
1	1

$2^{2^K} \rightarrow$ possible Boolean functions of k inputs

x1	x2	x1 ∧ x2
0	0	0
0	1	0
1	0	0
1	1	1

$p = 0.25$

p	q	p ∨ q
0	0	0
0	1	1
1	0	1
1	1	1

$p = 0.75$

Lookup tables (LUT)

p: bias, or proportion of "1's" (or "0's") in output

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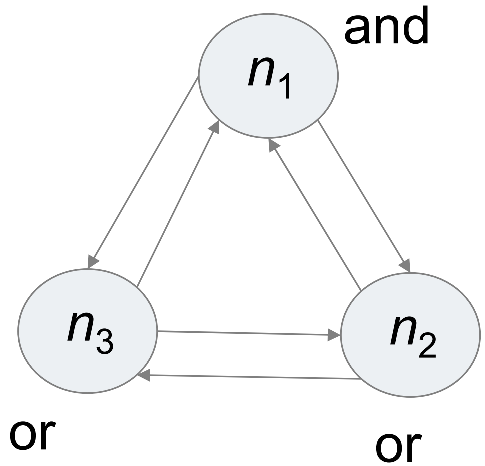
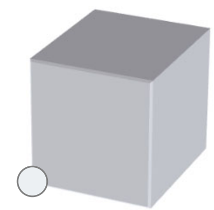
simple Boolean network

Small NK-network of 3 variables



p	q	p ∧ q
0	0	0
0	1	0
1	0	0
1	1	1



State space

p	q	p ∨ q
0	0	0
0	1	1
1	0	1
1	1	1

t				t+1			
	n_1	n_2	n_3	n_1	n_2	n_3	
0	0	0	0	0	0	0	0
1	0	0	1	0	1	0	2
2	0	1	0	0	0	1	1
3	0	1	1	1	1	1	7
4	1	0	0	0	1	1	3
5	1	0	1	0	1	1	3
6	1	1	0	0	1	1	3
7	1	1	1	1	1	1	7

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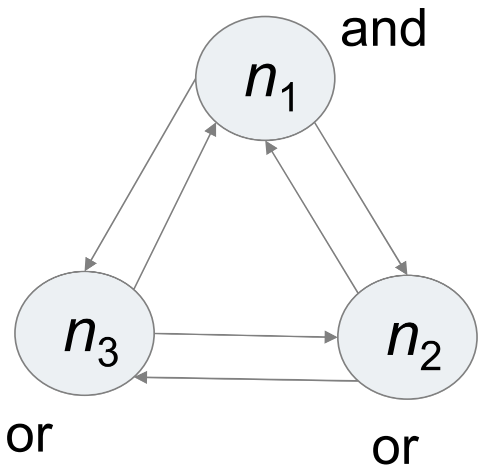
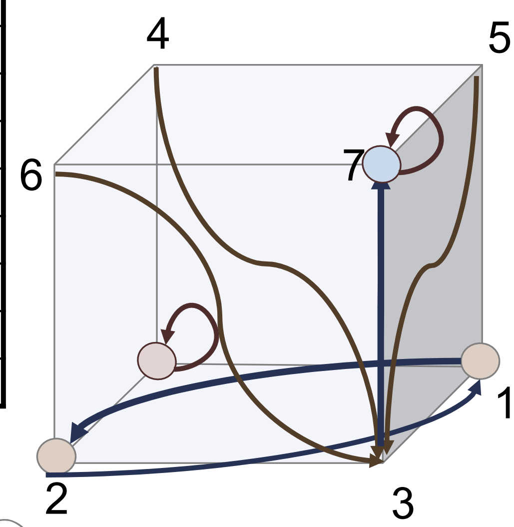
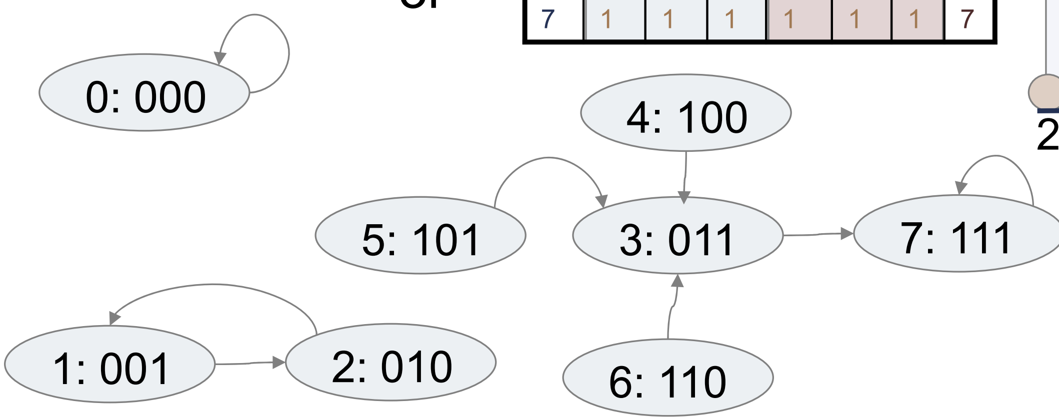
Attractors and state-space



	t			t+1			
	n_1	n_2	n_3	n_1	n_2	n_3	
0	0	0	0	0	0	0	0
1	0	0	1	0	1	0	2
2	0	1	0	0	0	1	1
3	0	1	1	1	1	1	7
4	1	0	0	0	1	1	3
5	1	0	1	0	1	1	3
6	1	1	0	0	1	1	3
7	1	1	1	1	1	1	7





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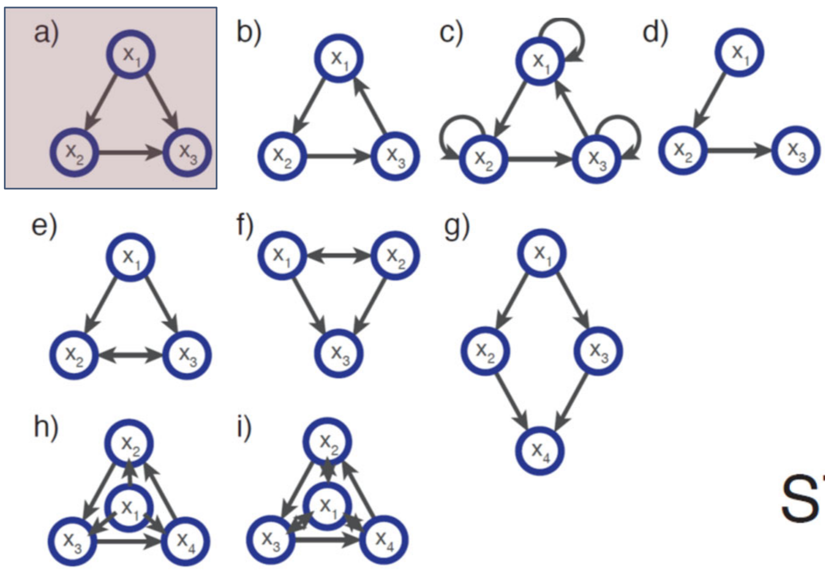
ensemble dynamics for same structure



different Boolean networks for same structure

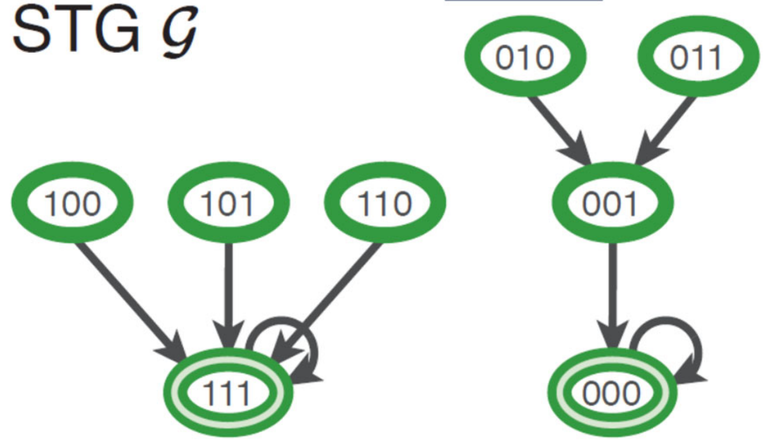
$$\prod_{i=1}^{N} 2^{2^{k_i}}$$

a) 64

Variable Logic

Variable	Logic
x_1	-
x_2	x_1
x_3	$x_1 \vee x_2$

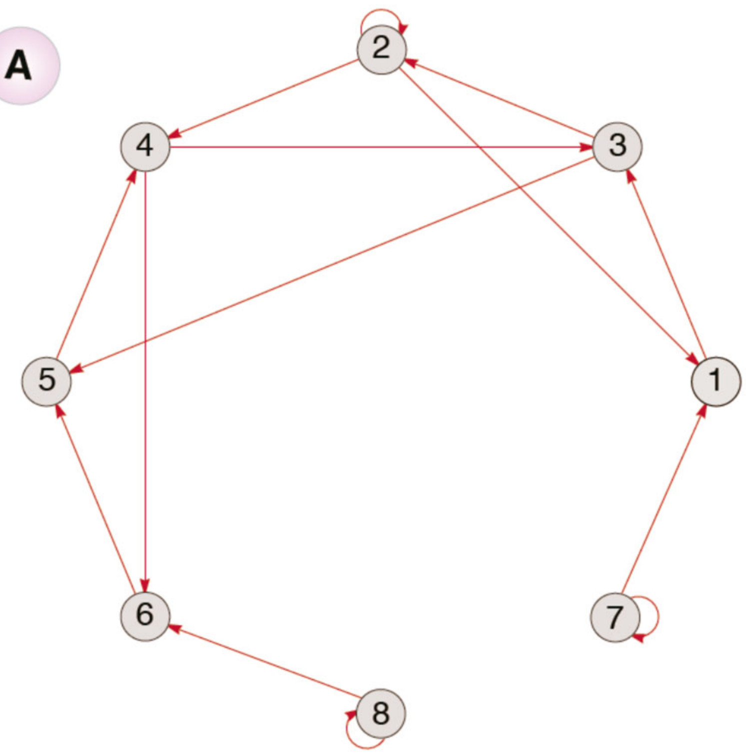
STG $\mathcal{G}$



Gates & Rocha [2016] *Sci Rep* 6, 24456

SimpleNet

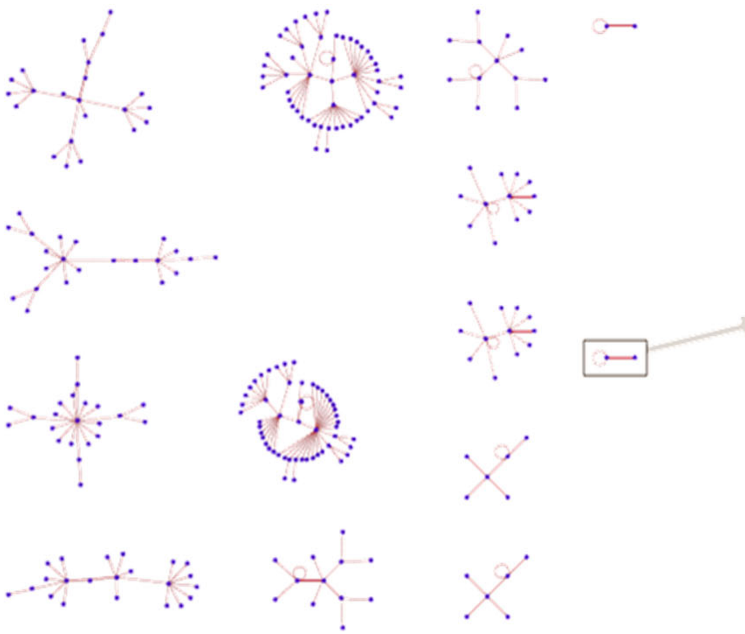
A



B

Node	Input Nodes	Logical Update Function	Truth Table 0,0	0,1	10	1,1
1	2, 7	$2 \barwedge 7$	1	1	1	0
2	2, 3	$2 \wedge 3$	0	0	0	1
3	1, 4	$1 \vee 4$	0	1	1	1
4	2, 5	$2 \vee 5$	0	1	1	1
5	3, 6	$3 \wedge 6$	0	0	0	1
6	8, 4	$8 \vee 4$	0	1	1	1
7	7	7				
8	8	8				

State-transition graph (basins of attraction)



Basin	Size	Attractor	Attractor Period
8	22	1,0,1,1,0,1,1,0 1,0,1,0,1,1,1,0 1,0,1,1,1,0,1,0	3
9	2	1,0,1,1,1,1,1,0	1
10	2	1,0,1,1,1,1,1,0	1
11	12	1,1,1,1,1,1,0,1	1
12	12	1,1,1,1,1,1,0,1	1
13	12	0,1,1,1,1,1,1,0	1
14	12	0,1,1,1,1,1,1,1	1

Basin	Size	Attractor	Attractor Period
1	6	1,0,1,0,0,0,0,0	1
2	52	1,0,1,1,1,1,0,1	1
3	6	1,0,1,0,0,0,1,0	1
4	52	1,0,1,1,1,1,1,1	1
5	22	1,0,1,0,0,1,0,0 1,0,1,0,1,0,0,0 1,0,1,1,0,0,0,0	3
6	22	1,0,1,0,0,1,1,0 1,0,1,0,1,0,1,0 1,0,1,1,0,0,1,0	3
7	22	1,0,1,1,0,1,0,0 1,0,1,0,1,1,0,0 1,0,1,1,1,0,0,0	3

There are 2^8=256 possible states but only a small set (14) of attractors

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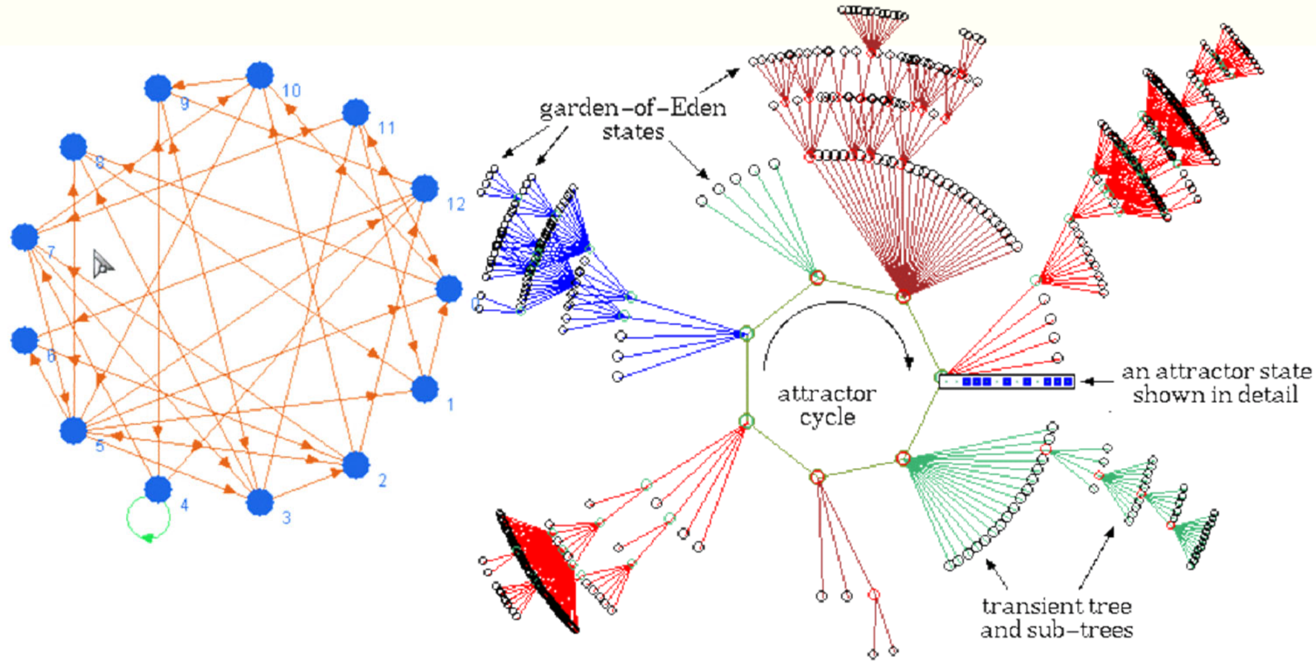
Example 13 variables



NK Boolean Network (N=13, K=3)

DDLab (Andy wuensche): http://www.ddlab.com/

There are 2^{13}=8192 possible states but only a small set of attractors

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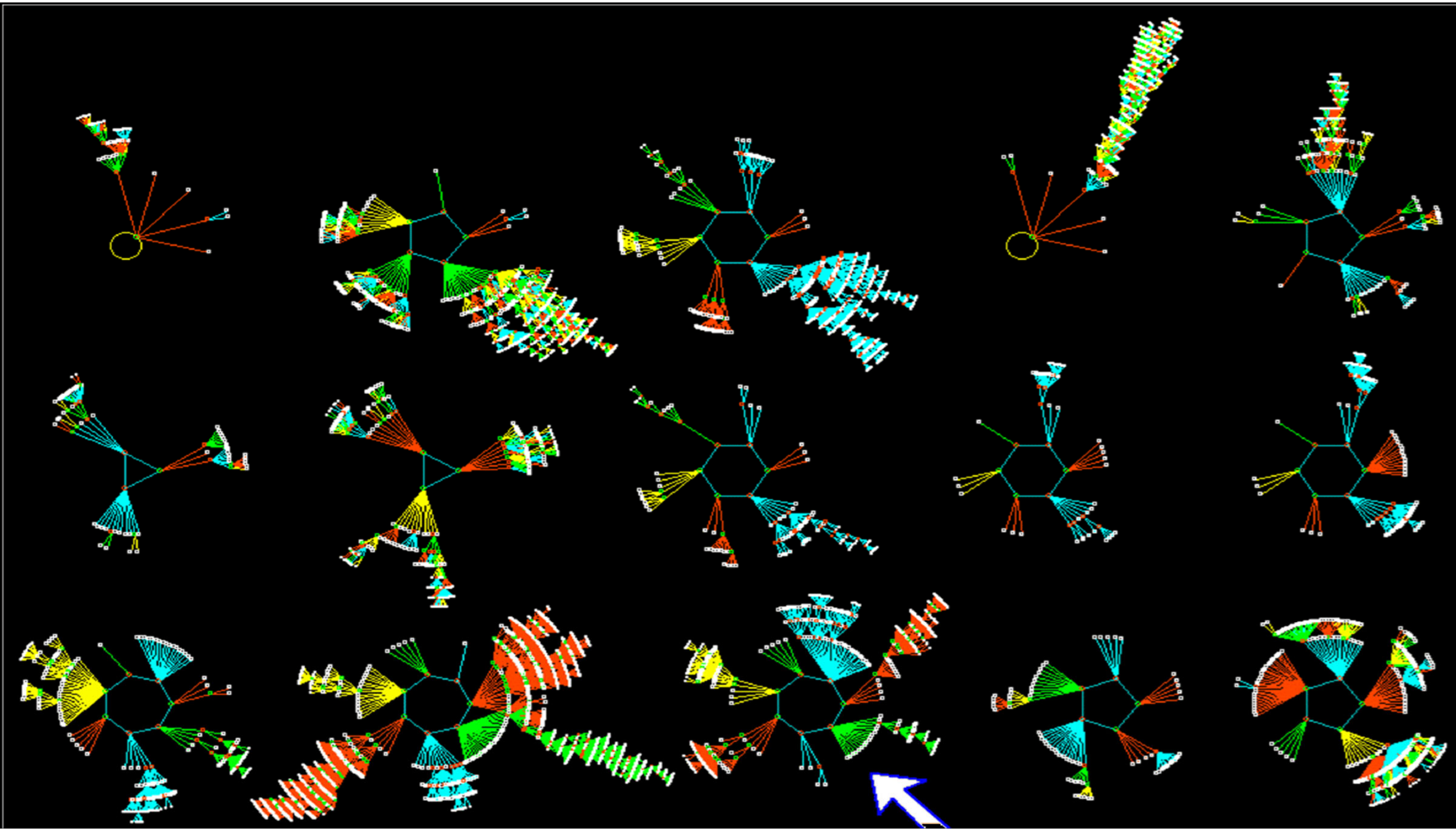
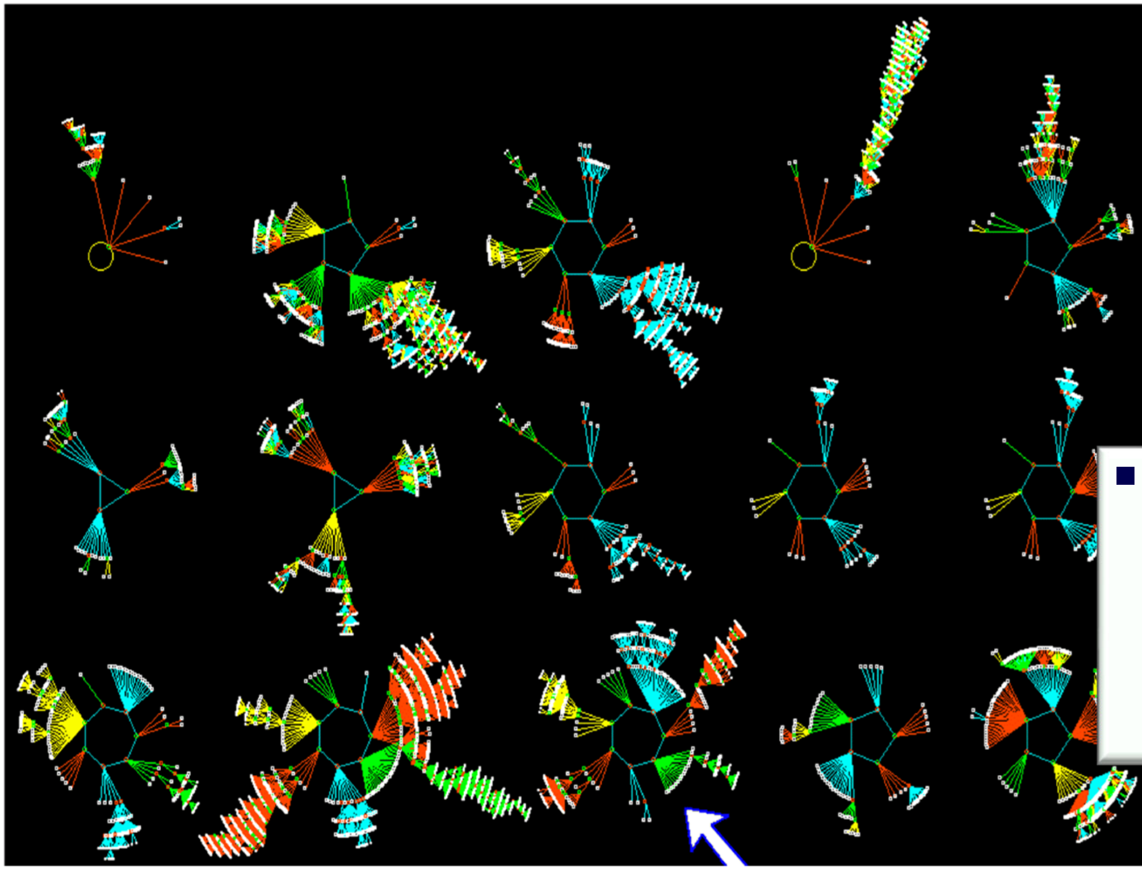


how to control?

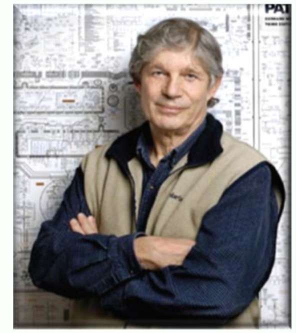


How to infer **controllability** if STG is too large to compute? From configuration to configuration, or attractor to attractor?

- The 2^{13}=8192 states in state space are organized into 15 basins
  - attractor periods ranging between 1 and 7.
  - The number of states in each basin is: 68, 984, 784, 1300, 264, 76,316, 120, 64, 120, 256, 2724,604, 84, 428.

readings

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press.
    - **Chapter 2**.



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- Papers and other materials
  - Optional
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall.
      - Chapter 2, all sections
      - Chapter 7, sections 7.3 – Cellular Automata
      - Chapter 8, sections 8.1, 8.2, 8.3.10
    - Flake's [1998], *The Computational Beauty of Life*. MIT Press.
      - Chapters 10, 11, 14 – Dynamics, Attractors and chaos